

Low-Density Cellular Concrete Void Filling

Deactivation and Decommissioning
Focus Area



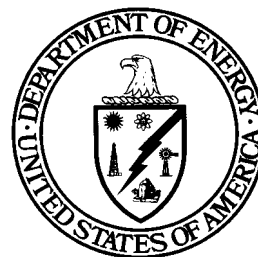
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Low-Density Cellular Concrete Void Filling

OST Reference #1846

Deactivation and Decommissioning
Focus Area



Demonstrated at
Fernald Environmental Management Project –
Buildings 1A and 30B
Fernald, Ohio



Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at <http://OST.em.doe.gov> under "Publications."

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SECTION 1

SUMMARY

Introduction

The United States Department of Energy (DOE) continually seeks safer and more cost-effective remediation technologies for use in the deactivation and decommissioning (D&D) of nuclear facilities. To this end, the Deactivation and Decommissioning Focus Area (DDFA) of the DOE's Office of Science and Technology sponsors Large-Scale Demonstration Projects (LSDPs) at which developers and vendors of improved or innovative technologies showcase products that are potentially beneficial to the DOE's projects and to others in the D&D community. Benefits sought include decreased health and safety risks to personnel and the environment, increased productivity, and decreased cost of operation.

Under the D&D Implementation Plan of the DOE's Fernald Environmental Management Project (FEMP), non-recyclable process components and debris that are removed from buildings undergoing D&D are placed in an on-site disposal facility (OSDF). Critical to the design and operation of the FEMP's OSDF are provisions to protect against subsidence of the OSDF's cap. Subsidence of the cap could occur if void spaces within the OSDF were to collapse under the overburden of debris and the OSDF cap. Subsidence may create depressions in the OSDF's cap in which rainwater could collect and eventually seep into the OSDF. To minimize voids in the FEMP's OSDF, large metallic components are cut into smaller segments that can be arranged more compactly when placed in the OSDF. Component segmentation using an oxy-acetylene cutting torch was the baseline approach used by the FEMP's D&D contractor on Plant 1, B&W Services, Inc., for the dismantlement and size-reduction of large metal components. Although this technology has performed satisfactorily, it is time-consuming, labor-intensive, and costly. The oxy-acetylene torch used in the process exposes workers to health and safety hazards including the risk of burns, carbon monoxide, and airborne contamination from combustion of residual lead-based paints and other contaminants on the surface of the components. Solvents used to remove paint from the components before segmenting them also emit highly flammable, noxious fumes.

This demonstration investigated the feasibility of placing large vessels intact in the OSDF without segmenting them. To prevent the walls of the vessels from collapsing under the overburden or from degradation, an innovative approach was employed which involved filling the voids in the vessels with a fluid material that hardened on standing. The hardened filling would support the walls of the vessels and prevent them from collapsing. This report compares the cost and performance of the baseline segmentation technology and the innovative void filling technology using low-density cellular concrete (LDCC).

Technology Summary

Baseline Technology

In-situ component segmentation is a fully developed process that is widely used throughout the DOE complex for preparing D&D debris for disposal. The technology used for segmenting components is an oxy-acetylene cutting torch. To reduce airborne contamination and the risk of fire, paint solvents are used to remove combustible paint from the sections of components that are to be cut with the torch. Components are then cut into segments according to the FEMP's OSDF waste acceptance criteria (WAC, see Appendix C) that stipulate the maximum dimensions of debris that can be placed in the OSDF to prevent excessive void volumes.



Innovative Technology

Void filling using LDCC is a fully developed and commercially available technology. LDCC has a lower density and a lower thermal conductivity than regular concrete. It is used extensively in the construction industry for both poured and pre-formed concrete roofs and walls and for backfilling trenches for water and sewerage lines that are susceptible to freezing. Some large-scale applications include

- Boston Logan Airport – 30,000 cubic yards of LDCC
- Niagara Falls – construction of raw water intake tunnels up to 10 feet in internal diameter and 2,000 feet long
- Yucca Mountain Project – construction of a hard rock tunnel 25 feet in diameter and for ground stabilization and void filling.

In the nuclear industry, LDCC is used for coating process vessels and components before dismantling them to suppress release of high levels of surface contamination. It is also used as a radiation shield on the outside of contaminated process vessels and components to reduce the levels of radiation outside the components.

As an alternative to component segmentation, void filling of intact components has the potential to reduce significantly the time taken to prepare D&D debris for placement in an OSDF and accelerate overall D&D schedules. It would also reduce the airborne contamination, worker health and safety risks, and personal protective equipment (PPE) requirements associated with using a cutting torch for component segmentation. If these objectives are met, the void filling technology could result in substantial savings for D&D projects. One drawback of this technology is the additional space required for storing intact components in an OSDF.

How It Works

LDCC is produced by integrating cement with an expanded foam instead of a sand/gravel aggregate. Air bubbles entrained in the foam create small air pockets in the concrete and lower its density. The density and strength of the LDCC are determined by the amount of foam incorporated into the cement. For the FEMP demonstration, the objective was to produce LDCC that was light enough to permit transportation of the filled vessels, yet strong enough to prevent collapse of the components. The FEMP Integrating Contractor Team (ICT) determined that a minimum compressive strength of 10 pounds per square inch was necessary to prevent collapse of components stored in the OSDF and avoid subsidence of the OSDF cap. The LDCC would also need to have a density of 30 pounds per cubic foot (lbs/ft³) so that filled vessels could be moved with a forklift and not require special equipment.

The LDCC used in the demonstration was generated by introducing an aerated protein-based surfactant, Mearl Geofoam, into a cement-water mixture. The Mearl Geofoam concentrate was first mixed with water in a tank and pressurized to 100 psi using compressed air. The pressurized solution was fed through a foam generator, and the resulting foam was added directly to a cement-water mixture on a concrete mixing truck (see Figure 1). The LDCC was then pumped to the void filling work area where it was injected into the vessels being filled (see Figure 2).

Components to be void filled were removed intact from Building 1A and placed in a temporary void filling work area in Building 30B. The LDCC was injected into the vessels in layers no more than four feet in depth, and each layer was allowed to set completely (approximately 72 hours) before adding the next. This was done so that the air pockets entrained in the foam aggregate would not collapse under the weight of the LDCC and increase its density.





Figure 1. The foam and concrete are combined in a concrete mixer, dispensed into a concrete hopper, and pumped to the void filling work area.



Figure 2. Technicians inject liquid LDCC into the vessel being void filled. The vacuum hose collects fumes and airborne contamination displaced from the vessel.

Demonstration Summary

The component segmentation and void filling technologies were demonstrated at the FEMP's Buildings 1A and 30B from May 16, 1996, through January 23, 1997. The actual time required to conduct the demonstration of both technologies was approximately 3 days. Baseline data were collected in May and June 1996; however, the tanks needed for the void filling demonstration could only be removed from Building 1A when the dismantlement schedule permitted. Consequently, the void filling demonstration could not be performed until January 23, 1997.

The purpose of the demonstration was to assess void filling of intact components as a viable alternative to component segmentation, for preparing D&D debris for placement in the FEMP's OSDF.

Ideally, components should be void filled after placing them in the OSDF. At the time of the demonstration, the FEMP OSDF was not yet able to accept debris for storage. Components had to be placed in a temporary void filling work area from which they were later transported for placement in the OSDF. The cost of labor and transportation to move filled components from the work area to the OSDF (or other storage facility) can be significant depending on the density of the void fill medium and the weight that it adds to the components. The weight of the void filled components was therefore an important consideration. It was imperative that the selected void fill medium be lightweight, while meeting the minimum compressive strength of 10 psi specified for debris placed in the FEMP OSDF. One of the candidate media selected for this demonstration was LDCC. The main advantages of using this medium are that it is lightweight and can be synthesized to meet the minimum compressive strength requirement. An alternative medium that was also selected for demonstration at the FEMP is polyurethane foam which is described in Section 4 of this report.

The key objectives of the demonstration were

- to determine whether expanded LDCC could be synthesized to meet the minimum compressive strength required for debris placement in the FEMP's OSDF and
- to assess the operational and economic feasibility of void filling intact components with expanded LDCC to prepare them for placement in the FEMP's OSDF versus the current baseline procedure of segmenting components using an oxy-acetylene torch.

Key Results

The key results of the FEMP demonstration were as follow:

- The LDCC void filling technology is a practical means of eliminating void spaces from vessels that are to be placed intact in an OSDF. As demonstrated at the FEMP LSDP, this technology is about 55 percent more productive than the baseline segmentation technology; however, it is about 2 percent more expensive to perform D&D work. Table 1 summarizes the key cost and performance factors that were measured during the demonstration.
- Void filling has the potential to permit faster removal of components from buildings, allowing other D&D work to continue and therefore accelerating D&D schedules. Although the unit cost of void filling is higher than the unit cost of segmentation, the considerably higher productivity of void filling has the potential to accelerate D&D schedules and realize savings that could not be objectively assessed by this demonstration. Such savings could offset or exceed the slightly higher cost, making the void filling technology more cost-effective than segmentation.

Table 1. Summary of key performance factors

	Segmenting using an Oxy-acetylene Torch (Baseline)	Void Filling with LDCC (Innovative)
Demonstration scale	694 ft ³	238 ft ³
Volume of vessels after treatment	22 ft ³	238 ft ³
Productivity	6.3 ft ³ /h	9.8 ft ³ /h
Variable Unit Cost for Performing D&D Work ***	\$22.21 / ft ³ *	\$22.69 / ft ³ **
Fixed Cost	\$0	\$8,776
Total (variable + fixed) Unit Cost (based on demonstration scale)	\$22.21 / ft ³	\$59.56 / ft ³
Break-even Point	Not applicable	

* Includes amortized capital cost of equipment

** Includes the rental cost of the equipment and supplies for generating LDCC.

*** Includes cost of labor, PPE, waste disposal, utilities and supplies.

Productivity

- Using the LDCC void filling technology, it was possible to fill voids in components at a rate of approximately 200 cubic feet per hour (i.e., the instantaneous production rate). However, when all the steps involved in preparing the components for placement in the OSDF (see Table 2 in Section 2) are taken into consideration, the overall productivity rate is 9.8 cubic feet per hour.
- Using component segmentation, it was possible to size-reduce empty vessels at a rate of 6.3 cubic feet per hour.

Cost of Performing D&D Work

- The variable unit cost of void filling components was 2 % higher than segmentation.
- Mobilization and demobilization costs for the void filling technology were significantly higher due to the cost of transporting the large pieces of LDCC equipment on and off site. Costs for mobilizing and demobilizing the oxy-acetylene torch were negligible.
- Due to the higher fixed costs associated with the LDCC void filling technology and its higher operating cost, there is no break-even point with the baseline segmentation technology.



- Void filling does not reduce the volume of the vessels treated. Segmentation reduced the volume of the vessels by a factor of 32, resulting in significantly lower waste disposal costs.

Performance

- The LDCC used in the FEMP demonstration had a density of about 45 pounds per cubic foot, much denser than the 25 pounds per cubic foot target that the contractor was requested to supply. Nonetheless, vessels filled with the higher density LDCC could still be moved easily using a forklift.
- The compressive strength of the LDCC exceeded 400 pounds per square inch after 28 days of curing, well above the 10 pounds per square inch minimum required for placement in the FEMP OSDF.
- The equipment used to produce the LDCC functioned well throughout the demonstration, and the problems encountered were minor and quickly resolved.
- The oxy-acetylene torch does not readily cut through rusted steel or cast iron, and in these instances, void filling might be a more productive alternative.

Personal Protective Equipment

- Segmentation is less productive than void filling with LDCC and requires a higher level of PPE (see Appendix D) due to the increased risk to personnel of fire and burn injury. PPE requirements and costs were therefore much higher for segmentation.

Health and Safety

- Chemicals used for generating LDCC are toxic and are a potential health risk during void filling.
- Segmentation using the oxy-acetylene torch presents risks of explosion, fire, and bodily harm. It also produces significant airborne contaminants such as carbon monoxide and lead.
- When vessels are void filled, the foam acts as a fixative for contaminants on the inner surfaces and reduces the risk of leaching if water permeates the OSDF.

Airborne Contamination

- Void filling produced considerably less airborne contamination than segmentation. Void filling generated minimal traces of toxic hexylene glycol vapor. The oxy-acetylene torch produced toxic carbon monoxide and elevated levels of airborne lead due to the combustion of residual lead-based paint and other contaminants on the surfaces of the components. Paint solvents used in the segmentation process are flammable and produce noxious vapors.
- During segmentation, residual contaminants on the inner surfaces of vessels normally become airborne. Void filling these vessels fixes the contaminants to the inner surfaces and prevents them from becoming airborne. Void filling would be a safer alternative to segmentation for preparing radioactively contaminated vessels for disposal.

Portability

- The equipment and drums of chemicals used to produce LDCC are mounted or transported on a truck and readily deployed to project sites that are accessible by such vehicles.



Permits, Licenses, and Regulatory Considerations

No special permits or licenses were required to operate the LDCC void filling equipment at the FEMP since it was owned and operated by the contractor, Pacific International Grout Company. An open flame permit was required to operate the oxy-acetylene torch.

The demonstrations involved the handling of hazardous chemicals and contaminated debris and the use of power tools and machinery. Technical support in the areas of radiation protection, health and safety, and regulatory compliance was provided by Fluor Daniel Fernald (FDF).

Technology Limitations and Needs for Future Development

Void filling is not a feasible option when components are simply too large or too heavy to be removed from buildings intact. At the FEMP site, intact removal is limited to components that are less than 15 feet in diameter and 25 feet long and weigh less than 10 tons. Almost all vessels at Plant 1 can be removed intact.

For the FEMP demonstration, components had to be void filled in a temporary work area and moved to a holding site pending final disposal. The density and added weight of the selected void filling medium were therefore major concerns. In applications where components can be placed directly in the OSDF before void filling, the density of the medium would not be as critical, and alternative media such as cement, contaminated soil, and other D&D debris could be used. The revised procedure would involve

- placing all components to be void filled directly in the OSDF;
- filling large voids with smaller components, waste material, contaminated soil, and other D&D debris;
- performing a mass filling of any remaining voids with an appropriate void fill medium.

This revised procedure could potentially increase productivity and reduce the cost of void filling, making it a cost-effective alternative to segmentation.



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Website

The FEMP Internet website address is <http://www.fernald.gov>

Other

All published Innovative Technology Summary Reports are available at <http://em-50.em.doe.gov>. The Technology Management System, also available through the EM50 website, provides information about OST programs, technologies, and problems. The OST reference number for Low-Density Cellular Concrete Void Filling Technology is 1846.

¹ As of 1 October 1997, several BWX technology companies, including B&W NESI, were consolidated into B&W Services, Inc., Lynchburg, Virginia.



SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process Definition

Hollow vessels placed in an OSDF could degrade and collapse over time and lead to subsidence of the OSDF's cap. Void filling entails filling the hollow spaces with a fluid material that hardens on standing. The void fill medium supports the sides of the vessels and prevents them from collapsing even if they degrade. LDCC was investigated as a potential void filling medium for eliminating spaces within debris placed in the FEMP's OSDF. The LDCC used in the demonstration was synthesized to meet or exceed the minimum compressive strength of 10 pounds per square inch recommended by the engineering team that designed the OSDF.

The current baseline approach for minimizing voids within debris is component segmentation using an oxy-acetylene torch. Figure 3 illustrates the process of void filling with LDCC.

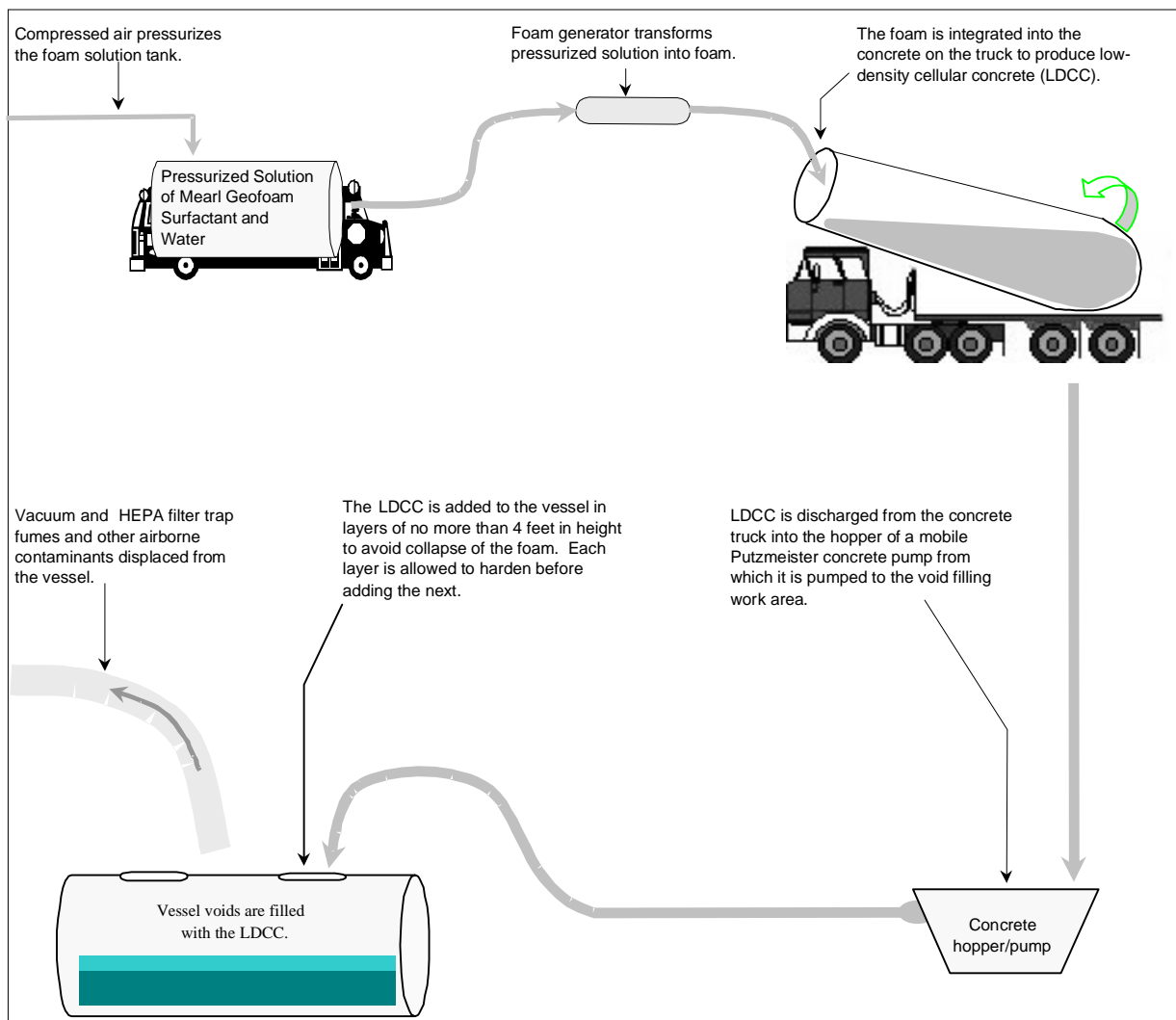


Figure 3. Schematic of the low-density cellular concrete void filling process.

Pacific International Grout Company was contracted to provide the LDCC for the demonstration as well as all necessary equipment, supplies, and trained technicians needed to perform the void filling exercise.

System Operation

LDCC is produced by adding a foaming agent to concrete. The foaming agent used was Mearl Geofoam, a protein-based surfactant. The concrete used was a mixture of cement and water only; no aggregate was added. Air bubbles entrained in the foam become integrated into the concrete when the two are mixed. The density of the concrete is adjusted by controlling the amount of foam added to the concrete.

Process Overview

Table 2 outlines the steps involved in segmenting and void filling vessels at the FEMP.

Table 2. Overview of segmentation and void filling processes

Segmentation	Void Filling
<ul style="list-style-type: none"> Strip paint from all areas to be cut with the torch. Secure segments to be cut with rigging, if necessary. Cut segments and remove them. Wash and dry segments. Dispose of segments. 	<ul style="list-style-type: none"> Strip paint from sections of vessels that must be cut to remove them from their housing. Secure vessels to be removed with rigging, if necessary. Cut vessels free of their housing. Move vessel by forklift to work area. Wash and dry vessels. Mobilize LDCC equipment. Test foam samples for compressive strength. Fill vessels with LDCC in layers. Allow each layer to expand, cool, and harden. Demobilize LDCC equipment. Dispose of vessels.

Void Filling Procedure

Vessels to be void filled were removed intact from Building 1A and placed in a temporary work area in Building 30B. The vessels were washed to remove surface contaminants and allowed to dry completely before void filling. They were then laid horizontally with their largest openings facing upwards, and all other openings were sealed with duct tape to prevent the void fill medium from leaking.

The LDCC was discharged from the concrete truck into the hopper of a mobile Putzmeister concrete pump from which it was pumped to the void filling work area. The LDCC was added to the vessels in layers approximately four feet deep, and each layer was allowed to harden before adding another. This ensured proper curing of the LDCC and prevented compression of the air bubbles trapped in the foam under the weight of the LDCC.

Table 3 summarizes the operational parameters and conditions of the void filling demonstration.



Table 3. Operational parameters and conditions of the void filling demonstration

Working Conditions	
Work area location	Building 30B of Plant 1 at the FEMP site.
Work area access	Accessible by forklift via roll-up doors to facilitate placement and removal of large intact components.
Work area description	The floor of work area was lined with poly sheeting to contain spillage of chemicals and liquid LDCC. The vessels to be filled were placed by forklift on wooden pallets on the floor of the work area.
Work area hazards	Hazardous chemical (Hexylene Glycol in Mearl Geofoam). Tripping hazards from hoses. Minimal airborne contamination. Heavy machinery and equipment.
Equipment configuration	The cement truck, foam unit, cement pump, and air compressor were operated outside Building 30B. The LDCC was pumped to the void filling work area via a high-pressure hose.
Labor, Support Personnel, Specialized Skills, Training	
Work crew	Three-person work crew required to <ul style="list-style-type: none"> - operate the concrete pump, - perform the void filling, - position the ventilation hose.
Additional demonstration support personnel	Full-time data taker Part-time Forklift Operator Full-time Radiation Technician Full time Health and Safety Officer
Specialized skills	Technicians experienced in using the LDCC equipment were contracted from Pacific International Grout Company to perform the void filling demonstration.
Training	Work crew members were briefed on health and safety issues related to the work site. Workers provided by Pacific International Grout Company were each required to complete 48 hours of site-specific training to become certified to enter the exclusion zone at the FEMP.
Waste Management	
Primary waste generated	Void filled intact components to be placed in OSDF. LDCC samples used for compressive strength tests.
Secondary waste generated	Disposable PPEs Poly sheeting used for lining the work area Protective wrapping for hoses HEPA filter and vacuum hose
Waste containment and disposal	Secondary waste was packaged in 55 gallon plastic bags for placement in the OSDF.
Equipment Specifications and Operational Parameters	
Portability	Heavy equipment. The cement pump and air compressor are normally mounted on a truck and transported to project sites. The void filling work area should be accessible to the truck. The high-pressure hoses and mixing gun can deliver the liquid LDCC mixture up to 300 feet from the truck.



Table 3. Operational parameters and conditions of the void filling demonstration (Cont'd)

Materials Used	
Work area preparation	Poly sheeting and duct tape for lining work area.
Personal protective equipment	Cotton coveralls, hood, and booties Rubber boots Rubber shoe cover Nitrile gloves and liners Impermeable Saranex disposable suit Nitrile gauntlets Respirator (half-face, charcoal filter air purifying)
Air filtration	Vacuum hose and HEPA filter
Chemicals for generating foam	10 gallons of Mearlcrete surfactant
Concrete	10 cubic yards of Portland type II delivered by a concrete mixer
Utilities/Energy Requirements	
Equipment	No additional utilities are required to power the LDCC-generating equipment.
Water	120 gallons
Work area	Six 110 volt, 1,500 watt space heaters were used to maintain a minimum work area ambient temperature of 40°F to avoid freezing of the chemicals.

Assessment of Technology Operation

Operational Strengths of the Void Filling Technology

Void filling with LDCC is a relatively safe process, and the equipment is easily operated by trained personnel.

Throughout the demonstration, the void filling equipment performed without any significant problems, and those that arose were minor and quickly resolved.

The equipment and chemicals were mounted on a truck and easily transported to the work site.

Operational Weaknesses of the Void Filling Technology

When void filling vessels, the LDCC must be added in layers, and each layer must be allowed sufficient time to cure and harden. This could result in significant idle time for the workers. During the FEMP, none of the vessels was greater than four feet in depth and this precaution was not necessary. However, shutdowns while the LDCC hardens could be avoided by processing several vessels at the same time and alternating between the vessels; i.e., while one layer is hardening in one vessel, another layer can be added to another vessel.

Other Considerations

At the time of the demonstration, the FEMP's OSDF had not yet been completed and vessels had to be void filled in a temporary work area and then transported to a holding area pending placement in the OSDF. Placing vessels directly into the OSDF and then filling them would expedite the process. In doing so, the weight of the fill medium would not be an issue and less expensive fill media could be used.



SECTION 3

PERFORMANCE

Demonstration Plan

Demonstration Objectives

The purpose of the demonstration was to assess void filling with LDCC as an alternative to the baseline component segmentation for preparing D&D debris for placement in an OSDF. The investigation assessed void filling, based on its performance, relative to the segmentation technology, in achieving the following demonstration objectives:

- increased productivity
- reduced cost
- reduced levels of airborne contamination
- reduced PPE requirements
- improved worker safety
- potential for reducing overall D&D schedules.

In addition, a minimum compressive strength of 10 psi for the LDCC would have to be achieved for it to be acceptable as a candidate void filling medium.

Demonstration Site Description

The void filling technology was demonstrated in Building 30B of Plant 1 at the FEMP site. The components to be void filled were removed intact from Building 1A and transported by forklift to Building 30B. The work area was lined with poly sheeting to contain spillage of chemicals and the liquid LDCC void fill medium. Portable heaters were used to maintain an ambient temperature of 40 °F in the work area. The LDCC generating equipment was located on a truck immediately outside Building 30B.

The component segmenting technology was demonstrated in Building 1A of Plant 1. The components were segmented in place using an oxy-acetylene torch. Ladders and a manlift provided access to the components, and rigging was installed to lower the segments as they were cut away.

Demonstration Boundaries

The void filling technology was demonstrated in September 1997. At the time of the demonstration, the FEMP's OSDF was not yet ready to accept debris for disposal. Components had to be placed in a temporary work area to be void filled and then transported to a holding area before placement in the OSDF. A more economical approach would have been to place the components directly into the OSDF before filling them; however, this could not be done due to the unavailability of the OSDF.

Treatment Performance

The segmenting technology was demonstrated on four cylindrical vessels/tanks with a combined total internal volume of 694 cubic feet. The void filling demonstration used three vessels with a combined total internal volume of 238 cubic feet (see Table 6). The vessels to be void filled had internal baffle plates that provided an opportunity to assess the technology's ability to fill between and around obstructions.

Assessment of LDCC as a Fill Medium

Debris placed in the FEMP's OSDF must be able to withstand a compressive force of at least 10 psi. Two batches of LDCC were used in this technology demonstration. Four samples were taken from each batch and sent to an off-site laboratory to have compressive strength measured. LDCC samples tested continually exceeded the minimum required compressive strength. Table 4 summarizes the test results.



Table 4: Results of the compressive strength tests performed on LDCC samples taken during the demonstration

	Compressive Strength in psi and Core Density in lb/ft ³ (in parentheses)			
Sample Number	Batch 1		Batch 2	
	7 Day Cure	28 Day Cure	7 Day Cure	28 Day Cure
#1	270 (44.8)		220 (44.8)	
#2	270 (44.8)		220 (48.9)	
#3		440 (44.8)		410 (48.9)
#4		460 (44.8)		400 (48.9)

Performance Relative to Demonstration Objectives

Table 5 summarizes the overall performance results of the void filling and component segmentation technologies for each of the demonstration objectives listed above.

Table 5. Performance comparison between component segmenting and void filling technologies

Performance Factor	Component Segmenting	Void Filling with LDCC
Productivity	6.3 ft ³ /h	9.8 ft ³ /h
Cost of performing D&D work	\$22.21 / ft ³	\$22.69 / ft ³
Airborne contamination	<ul style="list-style-type: none"> Carbon monoxide Paint remover vapors Carbon soot Airborne lead and uranium (up to 420% of Derived Air Concentration (DAC)); average 140 % of DAC. 	<ul style="list-style-type: none"> Traces of LDCC production chemicals (less than 2 ppm MDI) Traces of airborne uranium-238 (less than 1.4 % of DAC).
	Note: Ambient airborne uranium within building 30B is typically less than 2% of DAC which translates to 4x10 ⁻¹³ microcuries per cubic centimeter (μCi/cm ³).	
PPE requirements	\$14.96 / h of D&D work performed or \$7.07 / ft ³ of void eliminated.	\$15.12 / h of D&D work performed or \$1.11 / ft ³ of void filled.
	The oxy-acetylene torch required more restrictive PPE, hence higher cost per hour. However, its higher productivity resulted in lower cost per unit of work.	
Worker safety	Risks from open flame, higher airborne contamination, combustible paint remover, and risk of falling.	Risks from handling hazardous chemicals and using heavy machinery to transport large components.
Overall D&D schedule	<p>Components were segmented in the building. This precluded other D&D work from taking place in the same area at the same time.</p> <p>Similar to void filling, schedules could potentially be accelerated if the components were first removed intact from buildings and then segmented.</p>	Components were removed more quickly from the building, permitting other D&D work to proceed, which could accelerate D&D schedules.



Productivity Rates Achieved During the Demonstration

Table 6 summarizes the productivity rates achieved by the component segmenting and void filling technologies. The productivity rates are based on the total process time taken to prepare the debris for placement in the OSDF (see Table 2), and not simply the speed at which the torch cuts, or the rate at which the LDCC can be pumped into the vessels.

Table 6. Productivity data for component segmenting versus void filling technologies

Component Segmenting *		Void Filling	
Component	Volume (ft ³)	Component	Volume (ft ³)
Settling tank	404	Vacuum tank	57
Overflow tank	198	Stainless steel tank #4	118
Water tank	75	Vacuum Tank	63
Filter	17		
Total Volume	694	Total Volume	238

Total Processing Time (3 person work crew)	328 man hours 109 work hours	Total Processing Time (3 person work crew)	73 man hours 24 work hours
Productivity	6.3 ft³ / h	Productivity	9.8 ft³ / h
Estimated Process Time for 1,000 ft³ of debris (based on 10h work day)	16 days	Estimated Process Time for 1,000 ft³ of debris (based on 10h work day)	10 days

* All tanks were constructed of 3/8-inch carbon steel.

The actual filling of the three vessels with LDCC took about one hour and 10 minutes at a fill rate of approximately 200 cubic feet per hour. However, when all steps required to prepare the vessels for placement in the OSDF are taken into consideration, the entire process took about 24 work hours, and the resulting productivity was 9.8 cubic feet per hour. The productivity achieved by the segmentation process was 6.3 cubic feet per hour.

Airborne Contaminants

Segmentation resulted in considerably higher levels of airborne contamination than void filling (see Table 5). When cutting with the torch, uranium contamination embedded in the surface of the components and residual lead-based paint were vaporized and became airborne. During the void filling demonstration, very low levels of uranium were recorded, but this was most likely due to the ambient uranium levels within Building 30B and not a result of the void filling demonstration.



SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Technology Applicability

Void filling with LDCC is a fully developed and commercially available technology. It is used extensively in the construction industry for both poured and pre-formed concrete roofs and walls and in the nuclear industry as a fixative for contaminants and as a shield for radiation.

As demonstrated at the FEMP, void filling with LDCC is an effective and productive means of eliminating voids in large components that are to be placed intact in an OSDF, but it costs more to perform D&D work than segmentation. Void filling with LDCC is about 55 % more productive than segmenting and poses significantly lower risk to workers and the environment. These benefits are very important to D&D work, and project managers should seriously weigh them against the nominal difference in cost of the two technologies, particularly in light of the fact that the void filling technology has the potential to accelerate project schedules and reduce medium- and long-term costs.

Competing Technologies

Other technologies that may be considered for preparing D&D debris for disposal include the following:

Segmentation Using an Oxy-gasoline Torch

The oxy-gasoline torch was demonstrated as a part of the FEMP LSDP. It is similar in operation to the oxy-acetylene torch but uses gasoline instead of acetylene as the fuel. During the cutting process, the oxy-gasoline torch oxidizes the steel 100 % to a granular slag that is readily blown from the cut allowing the flame to penetrate deeper into the cut. As a result, the oxy-gasoline torch is able to cut thick metal faster and cleaner than the oxy-acetylene torch. At metal thicknesses above four inches, the oxy-gasoline torch is about three times as fast as the oxy-acetylene torch. Other benefits of the oxy-gasoline torch include

- lower airborne contamination,
- lower fuel cost,
- reduced risk of explosion (liquid gasoline cannot burn or explode on impact; acetylene can), and
- no risk of backflash up the fuel line.

The oxy-gasoline torch is manufactured by Petrogen International, Ltd., of Richmond, California; telephone (510) 648-4785.

Void Filling Using Polyurethane Foam

This technology was also demonstrated as part of the FEMP LSDP. The process is similar to void filling with LDCC except that the medium employed is polyurethane foam. The polyurethane foam is produced by combining two liquid chemicals, polymeric diphenylmethane diisocyanate (MDI) and polyol blend. The result is a lightweight liquid foam mixture that expands and hardens on standing. The hardened foam has a density of about 2.1 pounds per cubic foot and a compressive strength of about 20 pounds per square inch. The productivity achieved using this technology at the FEMP LSDP was 3.5 cubic feet per hour, less than that achieved by either void filling with LDCC (9.8 cubic feet per hour) or segmentation with an oxy-acetylene torch (6.3 cubic feet per hour).

Patents/Commercialization/Sponsor

This demonstration involved the use of a fully developed technology. Void filling with LDCC is not a patented process. It integrates a number of existing technologies, such as concrete mixing and foam production.



SECTION 5

COST

Introduction

This analysis compares the cost of preparing large D&D components for placement in the FEMP's OSDF either by segmenting them with an oxy-acetylene torch or by void filling the intact components with LDCC. The purpose of the cost analysis is to present validated demonstration data collected during the LSDP in a manner that will enable D&D decision-makers to select the preferred technology for their specific applications. It strives to develop realistic estimates that are representative of work performed within the DOE complex; however, the reader should be aware that it is only a limited representation because it uses only data measured during the limited duration and under the specific conditions of the FEMP demonstration. Some of the observed costs have been eliminated or adjusted to make the estimates more realistic. These adjustments have been made only when they do not distort the fundamental elements of the observed data (i.e., they do not change productivity rates, quantities, work elements, etc.) or when activities are atypical of normal D&D work. Additional cost information and demonstration data are contained in the *Detailed Technology Report for the Low-Density Cellular Concrete Void Filling Technology*, FEMP, 1997, which is available on request from the FEMP.

Methodology

Cost and performance data were collected for each technology during the demonstration. The following cost elements were identified in advance of the demonstration, and data were collected to support a cost analysis based on these elements:

- **Mobilization** includes the cost of transporting equipment to the demonstration site, training the crew members to use the equipment, providing crew members (including vendor-provided personnel) with FEMP site-specific training, constructing temporary work areas, and installing temporary utilities.
- **D&D Work** includes the cost of labor, utilities consumed, supplies, and the rental or amortized cost of using the equipment during the demonstration. The rental cost of the LDCC equipment includes the chemicals used in synthesizing the foam.
- **Waste Disposal** is the cost of disposing of the primary waste products of the demonstration such as the segmented components, the void filled tanks, and the LDCC samples from the compressive strength tests (see Table 7 for resulting waste volumes).
- **Demobilization** includes removal of support equipment such as riggings and manlifts, disconnection of temporary utilities, dismantlement of temporary work areas (including associated secondary waste disposal), and equipment decontamination and removal from the site.
- **Personal Protective Equipment** includes the cost of all protective clothing, respirators, etc., worn by crew members during the demonstration.

Measurement of D&D Work

The objective of the segmentation and void filling demonstrations was to eliminate void spaces from D&D debris before placing them in an OSDF. The productivity of the technologies was therefore determined based on how quickly they could achieve this objective. In the case of void filling, productivity was a direct measurement of the volume of void spaces filled over a period. The productivity of the segmentation technology was the rate at which void spaces were eliminated by segmenting the components, i.e., the difference in the estimated volume of the debris before and after segmentation.



Measurement of Costs

The fixed cost elements (i.e., those independent of the quantity of D&D work, such as equipment mobilization and demobilization – see Appendix D) were calculated as lump sums. The variable cost elements (i.e., those dependent on the quantity of D&D work, such as labor costs) were calculated as costs per cubic foot of void eliminated from the vessels.

For the oxy-acetylene torch which was owned by the D&D contractor, equipment costs were based on ownership. Hourly equipment rates were calculated based on the procedure outlined in EP 1110-1-8, *Construction Equipment Ownership and Operating Expense Schedule, Region II*, U.S. Army Corps of Engineers, September 1997. Hourly rates were calculated using the capital cost of the torch (\$299), a discount rate of 5.6%, an estimated equipment life of 10,000 operating hours as advised by the vendor, and an estimated annual usage of 1,040 hours.

The equipment, chemical (Mearl Geofoam), and concrete used to produce the LDCC were supplied by the vendor under a service contract that covered the cost of all required supplies and rental of the LDCC generating equipment.

Costs for other materials and supplies used during the technology demonstrations were estimated by the FEMP ICT. Costs for the placement of waste in the FEMP OSDF that is under construction were estimated by FDF.

Where work activities were performed by the D&D contractor, labor rates used were those in effect at the FEMP at the time of the demonstration. Contractor indirect costs were omitted from the analysis since overhead rates can vary greatly among contractors and locations. Site-specific costs such as engineering, quality assurance, administrative costs, and taxes were also omitted from the analysis. Where appropriate, D&D decision-makers may modify the FEMP base unit costs determined by this analysis to include their respective site-specific indirect costs.

PPE costs are duration and technology dependent. Four changes of PPE clothing were required for each crew member per day. Reusable PPE items were estimated to have a life expectancy of 200 hours. Disposable PPE items were assumed to have a life expectancy of 10 hours - the length of the daily shift. The cost of laundering reusable PPE clothing items is included in the analysis (see Appendix D).

Cost Analysis

Table 7 summarizes the costs associated with the segmentation and void filling technologies. Details of these costs are presented in Appendix D.

Note, the capital cost of using the oxy-acetylene torch for the duration of the demonstration is negligible (approximately \$0.03 per hour) and was excluded from the analysis.

The unit costs for elements that are dependent on the quantity of work performed are based on the cost of performing one unit of work, i.e., the cost of eliminating one cubic foot of void space from empty/unsegmented vessels. For example, Table 7 shows that the segmentation technology eliminated 694 cubic feet of void spaces and resulted in 22 cubic feet of waste (segmented vessels). The total disposal cost for 22 cubic feet of segmented vessels at \$8 per cubic foot is \$176. Therefore, the unit cost for eliminating one cubic foot of void space is $\$176 \div 694 = \0.25 per cubic foot.



Table 7 Costs of using the void filling and component segmentation technologies

Cost Elements	Segmenting			Void Filling		
	Fixed Costs ¹	Variable Costs ²	Unit Costs ³	Fixed Costs ¹	Variable Costs ²	Unit Costs ³
Mobilization ¹	\$0	-	-	\$6,755	-	-
D&D Work ²	-	\$10,331	\$14.89 / ft ³	-	\$2,162	\$9.08 / ft ³
Waste Disposal ²	-	\$176	\$0.25 / ft ³	-	\$2,974	\$12.50 / ft ³
PPE ²	-	\$4,907	\$7.07 / ft ³	-	\$264	\$1.11 / ft ³
Demobilization ¹	\$0	-	-	\$2,021	-	-
Total	\$0	\$15,414	\$22.21 / ft³	\$8,776	\$5,400	\$22.69 / ft³

Quantity of D&D Work	694 ft ³		238 ft ³	
Resulting primary waste volume	Segmented vessels Other	22 ft ³ -	Unsegmented vessels LDCC samples (trash)	238 ft ³ 22 ft ³
FEMP OSDF Waste disposal rates	Segmented vessels Unsegmented vessels Trash		\$ 8.00/ft ³ \$12.10/ft ³ \$ 4.30/ft ³	

1. These costs are independent of the quantity of D&D work performed and therefore not included in unit costs.
2. These costs are dependent on the quantity of D&D work performed.
3. Based on the cost of eliminating one cubic foot of void space.

Fixed Costs

Mobilization costs were higher for the LDCC void filling because the equipment consists of several large pieces that must be transported to the site. In addition, the vendor personnel were each required to complete 48 hours of site-specific training in order to become certified to enter the exclusion zone at the FEMP. No costs were identified for mobilization of the oxy-acetylene torch because it was already at the site and D&D contractor personnel already possessed the required training. Even if this were not the case, mobilization costs would have been negligible because the torch equipment is easily transported and requires minimal training.

Demobilization costs were higher for LDCC void filling due to the amount of equipment that had to be moved off-site. Neither technology required any significant equipment decontamination.

Fixed costs are not included in the unit costs of operating either technology (see Table 7).

Variable Costs

The unit cost of performing D&D work was higher for the segmenting technology due to its lower production rate and consequent higher labor demand.

The unit cost of waste disposal was significantly lower for segmentation because this technology actually reduces the volume of the vessels by a factor of almost 32, whereas void filling does not reduce the volume of the vessels. Thus, for a given amount of D&D work, void filling produces 32 times as much primary waste volume as segmentation. In addition, the cost of placing waste in the FEMP OSDF is about 50% higher for large unsegmented vessels/components due to the additional work required to handle these large items and to backfill them after they are placed in the OSDF.

The PPE unit cost for segmentation was almost seven times that for void filling. Segmentation required a higher level of PPE that is more expensive per work shift than required for void filling (see Appendix D).



Furthermore, the production rate for segmentation is about 56 % lower than void filling, requiring more work shifts to complete a given amount of D&D work and proportionately more PPE usage.

Comparative Unit Costs

The comparative unit costs for the competing technologies are

- \$22.21/ft³ – segmenting with oxy-acetylene torch
- \$22.69/ft³ - void filling with LDCC

For the demonstrated application, LDCC void filling costs 2.1 % more than the baseline alternative. Since the fixed and variable costs are always greater for void filling, there is no break-even point with the baseline technology.

Cost Variable Conditions

The DOE complex presents a wide range of D&D work conditions. The baseline and innovative technology estimates presented in the analysis are based on a specific set of conditions and work practices found at Fernald Plant No. 1. Table 8 presents some of the FEMP-specific factors that have a direct bearing on the costs of segmentation and void filling. This information is intended to help the technology user to identify work differences that can result in cost differences.

Table 8. Summary of cost variable conditions

Cost Factor/Variable	Segmentation	Void Filling
Scope of Work		
Quantity D&D work	694 cu ft	238 cu ft
Debris treated	Tanks constructed of 3/8-inch carbon steel.	Tanks constructed of 3/8-inch carbon steel and 3/8-inch stainless steel.
Work Area		
Outside temperature(°F)	< 32	< 32
Ambient temperature (°F)	40	40
Work area access	The components were segmented in place, lowered using chain rigging, and removed with a forklift.	The work area was accessible by forklift for moving the large vessels in and out of the area.
Demonstration Plan		
Work process		A low-density medium was used because the components had to be void filled in a temporary work area and then transported for placement in the OSDF. Void filling directly in an OSDF would improve productivity and reduce costs. In addition, a less expensive medium could be used.
Other		
Capital cost of equipment	\$299	Estimated \$20,000
Estimated cost of labor	\$30/h	\$30/h



SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

The regulatory/permitting issues related to the operation of the LDCC Void Filling Technology at the FEMP Building 30B site are governed by the following safety and health regulations.

- **Occupational Safety and Health Administration (OSHA) 29 CFR 1926**

- 1926.300 to 1926.307 Tools – Hand and Power
- 1926.400 to 1926.449 Electrical – Definitions
- 1926.28 Personal Protective Equipment
- 1926.52 Occupational Noise Exposure
- 1926.102 Eye and Face Protection
- 1926.103 Respiratory Protection

- **Occupational Safety and Health Administration (OSHA) 29 CFR 1910**

- 1910.211 to 1910.219 Machinery and Machine Guarding
- 1910.241 to 1910.244 Hand and Portable Powered Tools and Other Hand-Held Equipment
- 1910.301 to 1910.399 Electrical Definitions
- 1910.95 Occupational Noise Exposure
- 1910.132 General Requirements (Personal Protective Equipment)
- 1910.133 Eye and Face Protection
- 1910.134 Respiratory Protection

Safety, Risks, Benefits, and Community Reaction

Since the void filling technology was designed specifically for generating LDCC, there are no regulatory requirements to apply CERCLA's nine evaluation criteria. Nonetheless, some evaluation criteria such as protection of human health and community acceptance are discussed below. Other criteria such as cost and effectiveness were discussed in Sections 3 and 5.

The heavy equipment and chemicals used to produce LDCC pose potential health hazards to workers. These hazards were averted by cordoning off work areas and requiring workers to wear appropriate personal protective equipment. The void filling technology substantially reduces levels of airborne contaminants and risk of burn associated with segmentation, thereby reducing the workers' exposure to these health hazards.

Waste generated by the void filling technology consisted of LDCC samples and plastic liners used to protect the work area. These were packaged in plastic bags and added to the existing low-level waste streams to be placed in the OSDF. The vacuum hose was also added to the waste stream.

Component segmentation and void filling involve similar activities, such as cutting metal with a torch, using rigging and a forklift to handle heavy components, and working on platforms and ladders above ground. Thus, both technologies have similar safety concerns; however, the risk to D&D workers is probably greater when segmenting due to the risk of burn, fire, and explosion while using the torch for extended periods. Segmentation also generated considerably more airborne contamination. A safety assessment performed on the void filling technology found that it involved "Standard industrial or construction hazards" which is the least critical hazard category. A further benefit of the void filling with LDCC is its higher productivity and potential to accelerate cleanup schedules.



Despite these benefits, community reaction to use of the void filling technology has not been positive due to concerns raised by local stakeholders and regulatory agencies. These concerns stem from the perception that large components may have an adverse effect on the engineered cap and liner system and thus the long-term stability of the OSDF. The FEMP has therefore decided not to place large void filled components in the OSDF.



SECTION 7

LESSONS LEARNED

Implementation Considerations

This void filling demonstration was conducted under the constraint that components would have to be void filled in a temporary work area outside the OSDF. The cost-effectiveness and productivity of the technology could be improved if the empty components were placed directly into the OSDF and then filled. In addition, if the components were filled after placement in the OSDF, there would be no need to minimize the density of the void filling medium, and lower cost foam, grout, or other fill could be used, provided it met the compressive strength requirement for the FEMP's OSDF.

Even if greater cost savings had been achieved with this technology, it is unlikely that it would have been implemented at the FEMP site due to concerns raised by the Fernald stakeholders after the technology had been selected and demonstrated at the FEMP. Their main concern was placing large objects in the OSDF and whether the spaces around these objects could be adequately compacted with soil to prevent future settling and subsidence of the engineered OSDF cap. Also of concern was the long-term effect that large heavy objects might have on the integrity and protectiveness of the impermeable OSDF lining.

Technology Limitations and Needs for Future Development

The void filling technology using LDCC performed without any significant technical or mechanical problems during the demonstration, and there appears to be no need for future development.

Technology Selection Considerations

- Void filling is not a feasible option when components are simply too large or too heavy to be removed from buildings intact.

Void filling components directly in an OSDF could make this technology more cost-effective than segmentation and possibly lead to savings in other areas such as D&D schedule acceleration. Another advantage of using LDCC to void fill vessels either before or after placing them in the OSDF is that the relatively lightweight medium facilitates re-positioning of the vessels within the OSDF.



APPENDIX A

REFERENCES

B&W Nuclear Environmental Services, Inc., *Environmental Safety and Health Plan*, B&W NESI, Lynchburg, Virginia.

Fluor Daniel Fernald, *Detailed Technology Report for the Urethane Foam Filling Technology*, Large-Scale Demonstration Project, U.S. Department of Energy's Fernald Environmental Management Project, Cincinnati, Ohio, September 1997.

Fluor Daniel Fernald, *Detailed Technology Report for the Low-Density Cellular Concrete Void Filling Technology*, Large-Scale Demonstration Project, U.S. Department of Energy's Fernald Environmental Management Project, Cincinnati, Ohio, September 1997.

U.S. Army Corps of Engineers (USACE), *Hazardous, Toxic, and Radioactive Waste Remedial Action Work Breakdown Structure and Data Dictionary*, USACE, 1996.

U.S. Army Corps of Engineers (USACE), *Construction Equipment Ownership and Operating Expense Schedule*, Washington, D.C., August 1995.

U.S. Army Corps of Engineers (USACE), *Productivity Study for Hazardous, Toxic, and Radioactive Waste Remedial Action Projects*, USACE, October 1994.



APPENDIX B

ACRONYMS AND ABBREVIATIONS

<u>Acronym/Abbreviation</u>	<u>Description</u>
CFR	Code of Federal Regulations
DAC	Derived Air Concentration
D&D	Deactivation and Decommissioning
dB	Decibels
DDFA	D&D Focus Area
DOE	Department of Energy
ESH	Environment, Safety and Health
°F	Degrees Fahrenheit
FDF	Fluor Daniel Fernald
FETC	Federal Energy Technology Center
FEMP	Fernald Environmental Management Project
FIU	Florida International University
ft ²	Square feet
ft ² /min	Square feet per minute
ft ³	Cubic feet
gpm	Gallons per minute
H&S	Health and safety
HEPA filter	High efficiency particulate air filter
HCET	Hemispheric Center for Environmental Technology (at Florida International University)
h	Hour
HTRW	Hazardous, toxic, radioactive waste
ICT	Integrating Contractor Team
IH	Industrial hygiene
in	Inch
lb.	Pound
LDCC	Low-Density Cellular Concrete
LLW	Low-level waste
LSDP	Large-scale demonstration project
μCi/cm ³	Microcuries per cubic centimeter
OEM	Office of Environmental Management
OSHA	Occupational Safety and Health Administration
OSDF	On-site disposal facility
OST	Office of Science and Technology
PPE	Personal protective equipment
ppm	Parts per million
psi	Pounds per square inch
USACE	United States Army Corps of Engineers
WAC	Waste Acceptance Criteria



APPENDIX C

WASTE ACCEPTANCE CRITERIA FOR PLACEMENT OF DEBRIS IN THE FEMP'S ON-SITE DISPOSAL FACILITY

Debris Category	Maximum Dimensions			Other
	Length (ft)	Width (ft)	Height (ft)	
General criteria for all categories of debris	10	10	1.5	<p>Maximum height = 1.5 ft. including projections.</p> <p>No dimension greater than 10 ft. including projections.</p> <p>No void spaces greater than 1 ft³.</p>
Accessible metals	10	4	1.5	
Inaccessible metals	10	4	1.5	
Painted light gauge metals	10	4	1.5	
Concrete	6	4	1.5	
Non-regulated asbestos containing material	8	4	1.5	Bundled stacks.
Regulated asbestos containing material	10	4	1.5	<p>Maximum volume per piece = 27 ft³.</p> <p>Pipes with diameter of 12 in. or more must be segmented so that no piece is greater than 12 in. in height.</p>
Miscellaneous materials	8	4	1.5	All miscellaneous materials must be compacted.



APPENDIX D

SUMMARY OF COST ELEMENTS

Table D.1. Details of major cost elements

Fixed Costs

Description	Quantity	Unit	Man hrs	Labor	Equipment	Materials	Other	Total
Segmentation	694	ft ³						
Mobilization			0	\$0	\$0	\$0	\$0	\$ 0
Demobilization			0	\$0	\$0	\$0	\$0	\$ 0
Total	694	ft³	0	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0
Void Filling	238	ft ³						
Mobilization			16	\$4320	\$13	\$22	\$2,400	\$6,755
Demobilization			19	\$555	\$15	\$0	\$1,451	\$2,021
Total	238	ft³	35	\$4,875	\$28	\$ 22	\$3,851	\$8,776

Variable Costs

Description	Quantity	Unit	Man hrs	Labor	Equipment	Materials	Other	Total	Unit Cost
Segmentation	694	ft ³							
D&D Work			328	\$9,931	\$0	\$400	\$0	\$10,331	\$ 14.89
Disposal			0	\$0	\$0	\$0	\$176	\$ 176	\$ 0.25
PPE			0	\$0	\$0	\$0	\$4,907	\$4,907	\$ 7.07
Total	694	ft³	328	\$9,931	\$ 0	\$ 400	\$5,083	\$15,414	\$ 22.21
Void Filling	238	ft ³							
D&D Work			38	\$1,289	\$262	\$595	\$16	\$2,162	\$9.08
Disposal			0	\$0	\$0	\$0	\$2,974	\$2,974	\$12.50
PPE			0	\$0	\$0	\$0	\$264	\$264	\$1.11
Total	238	ft³	38	\$1,289	\$262	\$595	\$3,254	\$5,400	\$22.69

Total Costs

Description	Quantity	Unit	Man hrs	Labor	Equipment	Materials	Other	Total	Unit Cost
Segmentation	694	ft ³							
Mobilization			0	\$0	\$0	\$0	\$0	\$0	\$0.00
D&D Work			328	\$9,931	\$0	\$400	\$0	\$10,331	\$14.89
Disposal			0	\$0	\$0	\$0	\$176	\$176	\$0.25
Demobilization			0	\$0	\$0	\$0	\$0	\$0	\$0.00
PPE			0	\$0	\$0	\$0	\$4,907	\$4,907	\$7.07
Total	694	ft³	328	\$9,931	\$ 0	\$ 400	\$5,083	\$15,414	\$22.21
Void Filling	238	ft ³							
Mobilization			16	\$4,320	\$13	\$22	\$2,400	\$6,755	\$6,755.00
D&D Work			38	\$1,289	\$262	\$595	\$16	\$2,162	\$9.08
Disposal			0	\$0	\$0	\$0	\$2,974	\$2,974	\$12.50
Demobilization			19	\$555	\$15	\$0	\$1,451	\$2,021	\$2,021.00
PPE			0	\$0	\$0	\$0	\$264	\$264	\$1.11
Total	238	ft³	73	\$6,164	\$290	\$617	\$7,105	\$14,176	\$59.56



Table D.2. Personal protective equipment costs and requirements
per crew member

Cost Assumptions:						
Daily Shift Length:	10 hours	hrs				
Useful Life of Reusable PPE Items:	200 hours	hrs				
Reusable PPE - Daily Requirements ¹			Segmentation using an Oxy-acetylene Torch (Baseline)		Void Filling with LDCC (Innovative)	
Item	Unit Cost	Unit	Quantity	Total Cost	Quantity	Total Cost
Cotton coveralls (yellow)	\$5.90	ea.	4	\$23.60	4	\$23.60
Cotton hoods (yellow)	1.16	ea.	4	4.64	4	4.64
Cotton shoe covers (yellow)	1.84	Pair	4	7.36	4	7.36
Leather welding apron	20.00	ea.	1	20.00	0	0.00
Leather welding gloves	7.00	Pair	1	7.00	0	0.00
Full-face respirators	174.00	ea.	4	696.00	4	696.00
Reusable PPE laundry costs ²	1.39	Load	1	1.39	1	1.39
Hourly Reusable PPE Cost				\$ 3.80	\$ 3.66	
Disposable PPE - Daily Requirements ³			Segmentation using an Oxy-acetylene Torch (Baseline)		Void Filling with LDCC (Innovative)	
Item	Unit Cost	Unit	Quantity	Total Cost	Quantity	Total Cost
Tyvek suits	\$4.09	ea.	0	\$0.00	4	\$16.36
Saranex suits	23.77	ea.	0	0.00	0	0.00
Mar-mac fire-resistant coveralls	3.36	ea.	4	13.44	0	0.00
Cotton glove liners	0.28	Pair	4	1.12	4	1.12
Cotton work gloves	0.54	Pair	0	0.00	0	0.00
Nytrile gloves	0.24	Pair	4	0.96	4	0.96
Rubber shoe covers	12.28	Pair	4	49.12	4	49.12
Rubber boots	29.30	Pair	0	0.00	0	0.00
Ear plugs	0.12	Pair	0	0.00	0	0.00
Ear protectors	18.72	ea.	0	0.00	0	0.00
Respirator cartridges	11.74	Pair	4	46.96	4	46.96
Hourly Disposable PPE Cost				\$11.16	\$11.45	
TOTAL HOURLY PPE COST				\$ 14.96	\$ 15.12	

¹Requires four changes per worker each day. Expected life = 200 hours.

²One day's reusable PPE for one crew member is one laundry load. Cost per laundry load is \$1.39. Data provided by Fluor Daniel Fernald.

³Requires four changes per worker each day. Expected life = 10 hours (the length of one shift).

